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Selecting the design of a high-temperature air heater for integrated gasification combined cycle

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Abstract. High temperature heat exchangers are needed in various energy technologies to increase their efficiency. The article is devoted to the optimization of the design of a high-temperature air heater used in the integrated gasification combined cycle plant, developed in Ural Federal University. In the air heater, air with a pressure of 2 MPa after the cycle compressor is heated by coal combustion to a temperature of 900°C before it is fed into the combustion chamber of a gas turbine. The air heater is developed as a pulverized coal fired boiler with air heating in tubular radiation-convection heating surfaces. The authors propose a new design of a high-temperature air heater, which allows reducing the cost of the expensive high-temperature part of the unit 1.8 times compared with the previous design. A computer simulation of the boiler section is carried out to verify the proposed design solutions.

1. Introduction

Despite the plans of Europe and the United States to reduce the use of coal, it continues to be the world's main energy fuel, moreover, according to the IEA, coal power in 2018, as in the previous one, grew by 3%, mainly due to Asian countries [1]. One of the promising directions for the development of coal energy is integrated gasification combined cycle (IGCC) that allows increasing the efficiency of power generation and, most importantly, achieving a significant reduction in emissions of harmful and greenhouse gases. Currently, many authors are engaged in the improvement of such facilities, offering solutions to enhance the gasification technology, gas cleaning and optimization of the flow diagram [2]. So in the UrFU's scheme [3], it is proposed to increase the efficiency of IGCC by unloading the gasification island due to air heating after the compressor in a heat exchanger with external combustion of coal. According to the calculations, the use of an air heater allows reducing the total coal consumption for IGCC by 15% and decreasing the mass and dimensional characteristics of the gasification island equipment by up to 30%.

This article considers the design optimization of the high-temperature air heater. There, due to the coal combustion, air after the cycle compressor with a pressure of 2 MPa is heated to a temperature of 900°C before it is fed into the combustion chamber of the gas turbine, the air flow rate being 553 kg/s. The air heater is developed as a pulverized coal fired boiler with air heating in tubular radiation-convection heating surfaces.



2. Main challenges in the air boiler designing

During air boiler designing 2 main tasks need to be solved:

- The choice of material for heating surfaces (first of all, high-temperature part).
- The maximum reduction in the size of expensive high-temperature elements of the boiler; and ensuring the conditions of their reliable operation near the operating temperatures close to the maximum permissible values.

2.1. The choice of material

At present, only high-temperature nickel alloys are commercially available for the manufacture of high-temperature heating surfaces; and in the future it will be possible to switch to pipes made of ceramic materials, for example, based on SiC. The temperature of air preheating for IGCC using high-temperature alloys, according to the assessment carried out [4], can reach 900°C. For reliable protection of heating surfaces from gas corrosion and wear by ash particles, it is advisable to apply a protective coating. For the use in an air boiler, targeted development of special alloys is required. However, pipes made from CrNi60WTi alloy, used for the manufacture of flame tubes, afterburner chambers and other parts for long-term work under temperatures of up to 1000-1050°C, are selected for research purposes from the pipe-rolled products produced by the domestic industry. The NiCrAlYTa and CrB₂ + 50% (Ni-Cr) compounds deposited on the samples by the method of gas-plasma spraying are studied as protective coatings. The possibility of improving the properties of coatings by laser melting after spraying is also investigated. Testing of coatings is currently carried out in natural conditions by placing samples on the supporting structures of a steam superheater of an operating pulverized coal fired boiler.

2.2. Design optimization

The cost of nickel alloys exceeds the cost of stainless steel by an order of magnitude and can reach up to \$70/kg [5], which requires minimization of the cost of high-temperature part of the boiler. To this end it is advisable to opt for pipes of a small diameter, which will significantly reduce the wall thickness, and therefore the cost of expensive alloys. Together with a decrease in the diameter of the pipes the heat transfer coefficient in the outlet sections of the boiler should be increased to further reduce the total costs. However, it is necessary to ensure reliable operation of the pipes, so the heat transfer coefficient of the air side must be several times higher than that of the outside.

3. Air boiler designing

Air boilers appeared in the middle of the last century as a part of a closed cycle gas-turbine plant, heating air with a pressure of 3 MPa to temperatures of about 700°C. Operating experience of such a facility is described in detail, for example, in [6]. These were U-shaped boilers with burners on the roof of the combustion chamber; on its walls there was the outlet radiation stage of heating surfaces; and the first stage with air heating to approximately 500°C was convective. However, copying this design with increasing power and heating temperature is irrational, as shown by an attempt to create such a boiler in the 90s in the Combustion 2000 project. A faster increase in air flow against to the cross-section of the furnace leads to the need to increase the pipes diameter from 32 mm in [6] to 57 mm in [7], and, consequently, the wall thickness. Thus, it is required to develop a new design of an air boiler.

Partly similar problems are solved when designing boilers for ultra-supercritical parameters. In [8] various designs of boilers are considered and the optimal one is chosen to minimize the length of expensive main steam pipelines to the turbine. Similarly, the reduction in the length of the hot air ducts to the gas turbine should be borne in mind during the designing of the high-temperature air heater. But due to the specifics of the air boiler, the structures considered in [8] are not suitable for use.

Earlier in [9] authors considered a convective high temperature air heater providing facilitating of the operating conditions of the output high-temperature surfaces. The disadvantage of the design is

that it neither noticeably enhances heat transfer nor reduces the size of the apparatus, and, in addition, it has higher operating costs. According to calculations in [4], when designing air heater output sections it is advisable to use pipes of small diameter of 10–20 mm and high air velocities over 30 m/s. This allows obtaining coefficients of heat transfer to compressed air over $600 \text{ W/m}^2\cdot\text{K}$, and placing the output high temperature surfaces of the boiler in the furnace.

As a result of calculations the new design of the unit with the placement of the outlet headers of the boiler in the lower part of the furnace is proposed. To minimize the dimensions of the boiler it is suggested to separate the furnace by high-temperature screens depending on the type of platen superheater on opposite sides of the furnace. This will allow placing a larger heat exchange surface in a constant volume and solving the problem of placing a large number (several thousands) of short (8–10 m) parallel-connected pipes of small diameter. The image of the boiler is shown in figure 1.

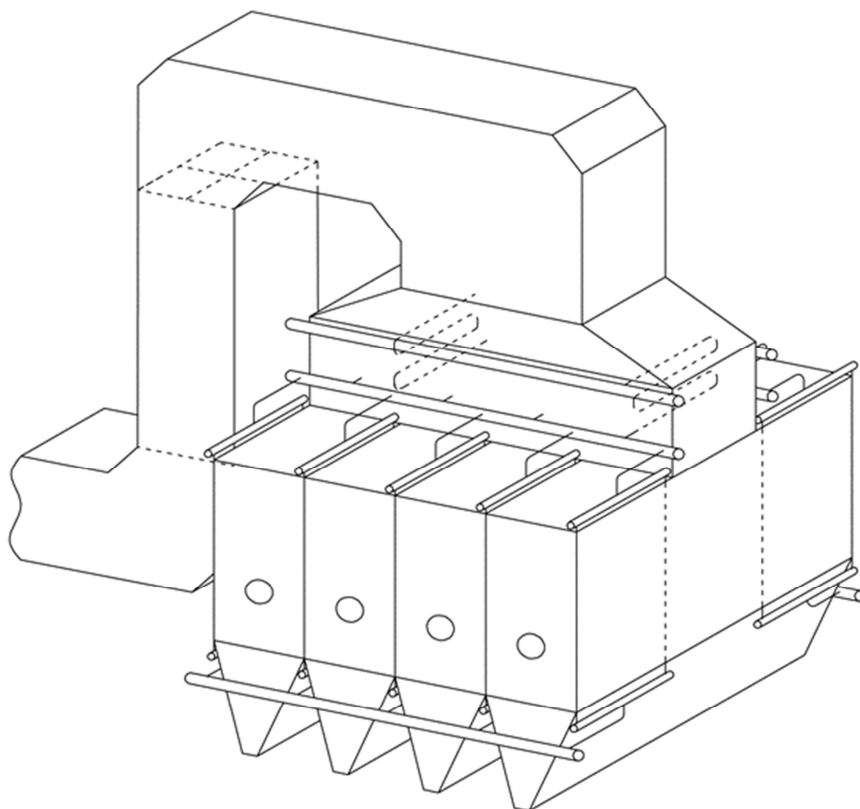


Figure 1. Air boiler conceptual design.

Figure 2 shows the simulation results of the boiler section using the SigmaFlame program. Data on the temperature of the outer surface of the section screens obtained by simulation and calculation also confirm that the wall temperature does not exceed the allowable values of $950\text{--}970^\circ\text{C}$ (given value of the ambient air temperature in the screens is 850°C), which means that the proposed design is suitable for further development.

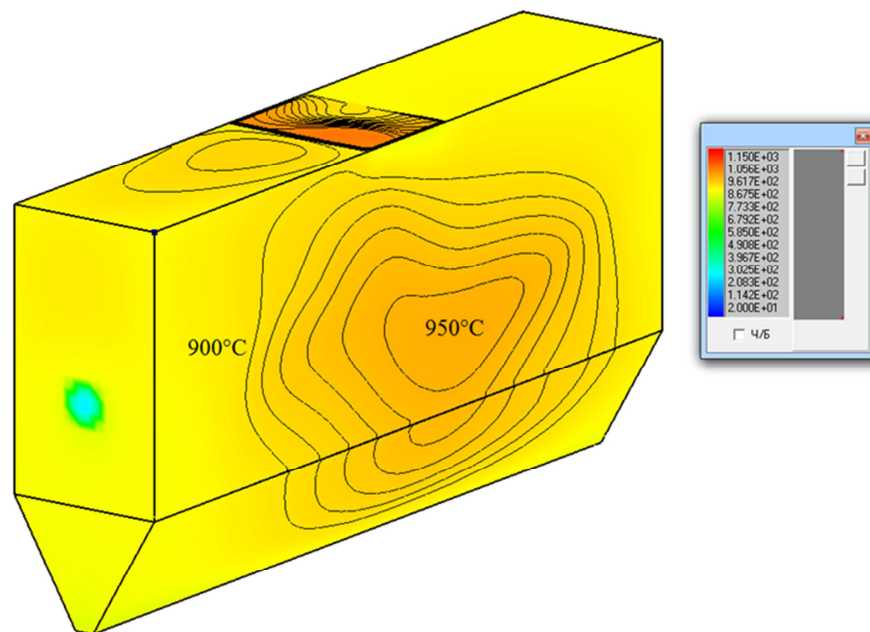


Figure 2. Field of surface temperatures of air boiler section.

4. Conclusion

A new design of a high-temperature air heater has been proposed for the use in the IGCC scheme. It will reduce the cost of the high-temperature part of the unit 1.8 times compared to the previously considered design; and as a result of further optimization the costs may be decreased even more. The output collectors of the air boiler are located in the lower part of the furnace, which simplifies the supply of hot air to the gas turbine and reduces the cost of air ducts. The simulation results confirm the possibility of ensuring the temperature of the outer surface of the furnace screens below the permissible values. Thus this design is deemed promising and can be recommended for further development. It is likely to be useful in the development of ultra-supercritical steam boilers or high-temperature heat recovery boilers.

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